20th European Conference on Fracture (ECF20)

Engineering critical assessment of clad pipeline installed by S-lay for the operation phase

Morten Hval a, Trond Lamvik a, and Ronny Hoff b

a Reinertsen AS, Leiv Eiriksson Senter, Postboks 6380 Sluppen, 7492 Trondheim, Norway
b IKM Ocean Design, 7010 Trondheim, Norway

Abstract

Pipeline material with internal cladding or liner of corrosion resistant material has become more customary in the later years as a replacement for carbon steel with high corrosion allowance due to the high corrosivity of unprocessed hydrocarbons. Clad material however, offer new challenges in the fracture assessment methodology due to inhomogeneous material, where the backing steel usually is low alloy carbon steel of 415 or 450 MPa yield stress and the clad layer basically has a significantly lower yield stress. In addition, the weld metal mechanical properties may only be partly overmatching compared to the base material. For operational conditions where the local material utilization exceeds the elastic limit, commonly used assessment methods based on analytical fracture models such as BS7910 might be inadequate for clad pipelines, and more detailed finite element modeling must be performed.

This paper addresses the relevant load scenarios for a clad steel pipeline installed by S-lay. A dedicated finite element program, LINKpipe has been used for the analyses to verify the acceptance criteria for defects in the girth welds. Input data for the analyses are taken from the detailed pipeline design calculations and material testing of the actual welding procedures of girth welds.

© 2014 The Authors. Published by Elsevier Ltd.
Selection and peer-review under responsibility of the Norwegian University of Science and Technology (NTNU), Department of Structural Engineering.

Keywords: Submarine pipelines; Clad material; ECA; S-lay; Defect acceptance criteria

Nomenclature

| BS          | Backing Steel |
| D/t         | Diameter to wall thickness ratio |
| CRA         | Corrosion Resistant Alloys |
1. Introduction

Submarine pipelines are subjected to different critical load scenarios from the welding fabrication through the installation phase and during the operation phase to the end of the design life. This may include:

1. Large plastic strains during reel-lay (typically 1-2%)
2. Fatigue loads in the lay catenary during installation, particularly for in-line components (Tees etc.)
3. Vortex induced vibration (VIV) fatigue loads in free spans at the seabed
4. Global buckling loads due to pressure and temperature variations
5. Interaction between fishing trawl gear or ship anchors during operations

All relevant load scenarios must be considered in a structural integrity fracture assessment of possible weld defects in the pipeline girth welds.

Until now, a generally accepted methodology for ECA analyses of solid pipe material has been available, DNV-OS-F101, Ref. /1/, which is based on the principles given in BS7910:2005, Ref. /2/. In the latest revision of DNV-OS-F101, some general guidelines are given also with respect to ECA and Clad/lined pipe materials. This, however restricts the methodology to be used for even-matched or over-matched clad and weld material properties.

In this paper a methodology is described using the Finite element based program LINKpipe for ECA analyses of CRA clad carbon steel. LINKpipe is developed by LINKftr and is a special purpose FE program for fracture mechanics analyses of cracks and defect in pressurized pipeline girth welds, Ref. /3/. The program is based on shell elements and uses line-spring elements for simulating the fracture response in pipelines, whether driven by static loads, global buckling, VIV, or corrosion. Ductile crack growth through the thickness and along the length direction of the crack is included. For further description and background of the program including validation cases, reference is given to the LINKftr WEB page, Ref. /4/, and Ref. /5/. LINKpipe also has an analytical module that calculates according to BS7910:2005.

2. Case Description

The particular case treated in this paper is a 16 inch OD CRA clad carbon steel pipeline installed by S-lay. The case does not have as high strains during installation as for reel-lay. Typical maximum strain during S-lay is in the range 0.25-0.3% total strain. The pipeline was, however, to be installed on the seabed over pre-installed buckle triggers in order to control the number and location of global buckles as well as the maximum strain level. Installing the pipeline over a preinstalled buckle trigger will also create a free span on both sides of the trigger. One possible problem for this pipeline is the potentially high buckle strains coinciding with high fatigue loads due to VIV in the adjacent free span or pressure/temperature fluctuations caused by shut-downs/shut-ins during production.
3. General Design Data

The general pipeline and material data are presented in Table 1. The real material tensile data were significantly higher than the minimum specified according to the governing standards. In addition to the difference in the tensile properties of the backing steel and the clad material, the weld material, which consisted of an Inconel Ni alloy consumable, resulted in rather inhomogeneous material properties. The tensile properties of the different materials were characterized by tensile testing. The upper bound true stress strain curves that were applied in the analyses are shown in Figure 1. The curves represent the stress strain curve at maximum operation temperature, 115 °C. It can be seen that the CRA material (316L) was significantly lower in strength than the backing steel and the weld metal, even if it was much higher than the minimum specified as given in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Backing steel</th>
<th>CRA Clad layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>N/A</td>
<td>DNV Grade 415</td>
<td>ASTM A240 UNS S31603</td>
</tr>
<tr>
<td>Wall thickness</td>
<td>mm</td>
<td>21</td>
<td>3</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>GPa</td>
<td>207</td>
<td>200</td>
</tr>
<tr>
<td>SMYS</td>
<td>MPa</td>
<td>415</td>
<td>170</td>
</tr>
<tr>
<td>SMTS</td>
<td>MPa</td>
<td>520</td>
<td>485</td>
</tr>
<tr>
<td>Fabrication method</td>
<td>-</td>
<td>Longitudinally welded (SAWL) clad plate</td>
<td></td>
</tr>
</tbody>
</table>

The mainline girth weld was a narrow gap multilayer weld performed with GMAW for the root pass, hot pass, fill and cap passes. The fracture toughness properties of the weld were characterized by J-R curves determined by SENT tests. It appeared that the lowest tearing resistance was in the center of the weld compared to the fusion line which had a significantly higher curve. Since LINKpipe required CTOD-R as input tearing resistance curve the J-integral values had to be converted to CTOD by using the equation:

$$CTOD = \frac{J}{\sigma_y \cdot d}$$  \hspace{1cm} (1)

Where $\sigma_y$ was the local yield stress (weld metal) and $d$ is a constraint factor usually between 1 and 2. For this material a value of 1.5 for $d$ was recommended by LINKpipe which resulted in the following CTOD-R relation:

$$CTOD = 0.38 \cdot \Delta d^{0.8}$$  \hspace{1cm} (2)

The following maximum strain values to be used in the ECA were determined by the detail design analyses:

Max strain during normal pipelay: $\varepsilon_{\text{max,install}} = 0.25\%$
Max strain at buckle trigger: $\varepsilon_{\text{max,buckle}} = 0.48\%$
Particularly the maximum strain at the buckle trigger was considered to be rather high as it was well above the yield strain. The value is, however considered to be rather conservative since the global analyses are based on a lower bound yield stress strain curve.

The fatigue stress ranges in the different phases are shown in Figure 2. Both the installation fatigue stress and the buckle fatigue stresses are in the same range while the VIV stresses are at a much lower level, however with a high number of cycles.

The design load data were the result of an iterative process that was carried out in order to eliminate unnecessary conservatism in the analyses and arrive at reasonable defect criteria for welding fabrication.

4. Methodology

The ECA methodology is to a large extent according to the 2012 edition of DNV-OS-F101 Appendix A, Ref. /1/, which makes further references to BS 7910, Ref. /2/. However, Ref. /1/ does not fully cover the given case with clad carbon steel. An exception was also the treatment of residual stresses in LINKpipe that is deviating from the method given in the 2012 edition of DNV-OS-F101. Reference is further given to Section 4.1 below for justification of how residual stresses have been included in the ECA analyses.

The intention has been to follow the development of a weld indication/defect from fabrication/NDT/repair through the relevant load stages until end of life. The obvious requirement is that an initial weld indication in a pipeline girth weld shall survive the whole lifetime with all the relevant loading stages (static or fatigue) of the pipeline without resulting in leakage or structural failure. Only the phase after installation will be addressed in this paper. It was considered that the probability of having the worst case flaw experiencing the worst case installation scenario and at the same time be at the worst possible location during operation was very low (less than $10^{-5}$), and hence, in agreement with DNV, regarded as negligible.

The weld/clad/backing steel mismatch was modelled in LINKpipe as close as possible to the real geometry using the material true stress-strain curves from Figure 1 and the tearing resistance curve of Equation (2) above with a weld geometrical misalignment of 1 mm.

No distinction was made in terms of tearing resistance for the various flaw locations, external, embedded or internal. It was verified that the clad layer had a higher tearing resistance than the parent metal, hence this was a conservative assumption. The lowest CTOD-R curve, which was for the weld metal, was therefore used in the analyses.

One issue that is not described in BS7910:2005 is the treatment of internal/external overpressure in ECA. The internal overpressure in pressurized pipes will increase the crack driving force compared to a pure uniaxial loading. Hence, if the internal pressure is high, it can be non-conservative to only consider the axial stresses. In order to assess the bi-axial effect a finite element program such as for instance LINKpipe must be applied.
4.1. Residual Stresses

The common approach to treat weld residual stresses as described in BS7910:2005 is to add a secondary stress equal to the yield stress to the applied primary stress. When the primary stress approaches the yield stress it is allowed to relax the secondary residual stresses, $Q_m$, by a factor according to the following equation:

$$Q_m = \left( 1.4 - \frac{\sigma_{ref}}{\sigma_f} \right) \cdot \sigma_y$$

where $\sigma_{ref}$, $\sigma_f$ and $\sigma_y$ are the local reference stress, the flow stress and the yield stress, respectively.

The residual stress equal to the yield stress reduces the elastic capacity of the cross section area, i.e. yielding occurs at loads below the yield limit compared to a corresponding structure without residual stress. This approach does not work for LINKpipe. Therefore, an alternative approach was chosen where the residual stresses are implemented for the line-spring elements only and thereby directly contributes to the crack driving force (CTOD). This method is strictly not in accordance with DNV-OS-F101. However, after having carried out several sensitivity analyses, the method described above was used in the ECA as it was considered to be the most appropriate method when using LINKpipe.

It is also acceptable according to DNV-OS-F101 to define the weld residual stresses by a “yield strain” (= $\sigma_y/E$) and simply add it to the maximum operational strain. This procedure was considered to be unsuitable when internal overpressure is applied as it gives overly conservative results. Relaxation of the residual stress according to Equation (3) is also possible when using LINKpipe. However, in order to maintain some degree of conservatism this was not applied in the analyses.

4.2. Loading Sequence

After being installed on the sea bottom the pipeline will first be exposed to temporary load. This period can last up to 2 years and needs to be included in the analyses, particularly the VIV loads in free spans which may result in fatigue crack growth. When production starts, the pipeline will be exposed to high pressure and temperature resulting in global buckling at the buckle triggers. At these locations the maximum strain of 0.48% will occur together with the VIV fatigue stress ranges as well as the stress fluctuations from the planned and unplanned production shut-in/shut-downs (buckling fatigue).

4.3. Defining the End-of-Life Failure Criteria

The coinciding occurrence of high maximum strain and high fatigue stresses may affect the fatigue life because high stress ranges at high maximum strain (at yield level) can result in higher fatigue crack growth than what is obtained according to Paris’ law which is used in most cases for ECA. An alternative approach would be to use the CTOD-R relation to calculate the fatigue crack growth based on ductile tearing in each stress cycle. This approach was considered to be very impractical and extremely time consuming. Instead a low $\Delta a_{max}$ value was specified as a “stop-criterion” in the analyses. Through sensitivity analyses this was considered to make the ECA analyses sufficiently conservative. The selection of an appropriate $\Delta a_{max}$ is discussed in more detail below.

Another important stop criterion was that the cracks were not allowed to grow from the inside beyond the CRA-Carbon Steel interface, resulting in a maximum allowable crack height of 3 mm equal to the thickness of the CRA layer. Furthermore, embedded defects were not allowed to break the internal surface.

4.4. Target Defect Criteria

The aim of the ECA was to verify that the weld defect acceptance criteria were equal or better than the target defect criteria defined by the workmanship criteria. The target defect criteria were defined according to Table 2.
Particularly the internal weld root defect criterion of 1.0 x 15 mm is very stringent due to the fact that fatigue cracks initiating from the weld root are not allowed to grow through the CRA layer neither by fatigue nor ductile tearing.

<table>
<thead>
<tr>
<th>Defect location</th>
<th>Maximum Defect Height [mm]</th>
<th>Maximum Defect Length [mm]</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near outer surface</td>
<td>3.0</td>
<td>25</td>
<td>Surface breaking defect not allowed</td>
</tr>
<tr>
<td>Embedded ½ WT</td>
<td>3.0</td>
<td>50</td>
<td>-</td>
</tr>
<tr>
<td>Embedded BS/CRA interface</td>
<td>3.0</td>
<td>50</td>
<td>Defect located in BS</td>
</tr>
<tr>
<td>Internal root defect</td>
<td>1.0</td>
<td>15</td>
<td>Surface breaking defect not allowed</td>
</tr>
</tbody>
</table>

Note 1: Embedded defect is to be re-categorized to surface defect if the ligament is less than half the defect height.

5. Results

5.1. Inner and Outer Surface Defects

The results of the ECA for surface defects are shown in Figure 3. The ECA curve for outer surface defects is very close, but slightly below the target defect size of 3 x 25 mm, while the ECA curve for the inner defects is well above. Further calculations for 25 mm long defect resulted in a critical height of 2.86 mm. One of the reasons why the ECA curve is lower for the inner surface defect is that defects are not allowed to grow by fatigue or ductile tearing through the CRA layer. Crack growth from the inside into the carbon backing steel may rapidly result in failure because of the corrosive process medium inside the pipeline.

5.2. Embedded Defects

Results from ECA analyses of embedded defects are shown in Figure 4. Both defect types are above the target defect size of 3 x 50 mm. The defect type denoted “BS/CRA”, which is located with the tip of the defect at the backing steel/CRA interface, is lower than the defect located in mid thickness (denoted “t/2”). The reason for this is that these types of defects are not allowed to grow by fatigue or ductile tearing through the CRA layer and reach the inner surface. The fatigue margin will therefore be lower and, hence, the allowable defect size is therefore also lower.
6. Sensitivity Analyses

The selection of ECA input parameters has to a large degree been made with worst cases data. This will result in conservative results. Ideally, probabilistic analyses should be done. This would, however, require a large amount of analyses and investigations with respect to determining the statistical distribution of stress-strain curve for the different materials, geometrical weld misalignment, tearing resistance, location of defect around the circumference and in the weld and the static and fatigue loads. Sensitivity analyses were therefore carried out to determine some of the inherent safety levels in the analyses in order to quantify the effect of the different input parameters. Since outer defects seems to be the most critical defect type as compared to the target defect criteria, most of the sensitivity analyses were carried out with an outer defect. Where relevant also cases with inner surface defect were included.

6.1. Influence of Weld Misalignment

The base case ECA analyses were carried out with a default weld misalignment of 1 mm. The default misalignment of 1 mm was compared with an alternative eccentricity of 0.5 mm. Since these pipes had very good dimensional tolerances 0.5 mm misalignment may be realistic in many cases.

Figure 5 shows the effect of comparing 1 mm eccentricity with 0.5 mm. At 25 mm defect length, the ECA curve is raised by about 0.5 mm. At longer cracks the difference is smaller. In case the misalignment turns out to be larger than 1 mm, which might happen if the welding is performed outside the requirements, the opposite effect with lower ECA curve would be the result.

6.2. Influence of Circumferential Flaw Location

The maximum stress and the stress ranges occur at the buckle crown at 3 or 9 o’clock position around the pipe circumference. If the weld defect is located offset compared to 3 o’clock (or 9 o’clock), the stresses will be reduced correspondingly. Figure 4.4-2 shows the result if the flaw is located at 2 or 4 o’clock (or 8 and 10 o’clock). In this case the maximum strain and the stress ranges will be reduced by 13.4 %. Figure 6a shows that the effect of clock position is very large, in the range of 1.0 mm at 25 mm length for outer defects. The effect will be even higher for higher offset values. For inner defects, Figure 6b, the difference is less significant (approximately 0.1 mm at 15 mm defect length).
6.3. Influence of Fracture Toughness

The base case analyses were performed with the lower bound CTOD-R curve given in Equation (2). If the CTOD-R curve is replaced by the average CTOD-R curve, where the constant 0.38 of Equation (2) is replaced by 0.48, the ECA curve will be significantly raised, as shown in Figure 7. The difference at 25 mm defect length is about 1.0 mm.

6.4. Effect of Maximum Strain in Buckle Crown

Initial analyses carried out showed that the maximum strain in the buckle crown affected the ECA curve to a certain extent depending on type of defect. In the present sensitivity analysis the maximum strain at the buckle crown has been reduced from 0.48 % to 0.4 %, corresponding to a reduction of 17 %. For outer surfaces defects as presented in Figure 8, the ECA curve is improved markedly, corresponding to more than 1.0 mm at the target defect length of 25 mm. Great effort was therefore put on having as accurate design calculations as possible, since too conservative analyses giving too high maximum strain level will greatly affect the defect criteria.

6.5. Sensitivity of $\Delta a_{\text{max}}$ (Maximum Allowable Ductile Crack Growth)

Important parameters in the ECA are the “stop” criteria, which determine when the analysis reaches a limit state. One of these limit states are the maximum allowable ductile tearing, $\Delta a_{\text{max}}$. This will determine the fatigue crack growth allowance for the initial defects.

The case with fatigue crack growth simultaneously with plastic deformation is a rather new load case when End-of-Life is considered. Normally, during reeling ECA, maximum 1 mm ductile tearing is considered as acceptable. However, reeling ECA is related to only a few cycle analyses and not fatigue. Using 1 mm maximum ductile crack growth during operation when the pipe also is bent up to and above yield is not recommended, as this may give non-conservative results. Too low $\Delta a_{\text{max}}$ values will on the other hand give too conservative results. A $\Delta a_{\text{max}}$ of 0.2 mm is based on sensitivity trials and experience from similar applications and is considered to be a reasonable max value.
The sensitivity analyses show the effect of selecting alternative \( \Delta a_{\text{max}} \) values from 0.1 mm – 0.3 mm. For outer surface defect the effect is considerable, Figure 9. An increase from 0.2 mm to 0.3 mm increases the acceptable defect height for a 25 mm long defect by more than 1 mm, while a reduction to 0.1 mm results in a very significant reduction of more than 1 mm.

7. Discussion

When the ECA methodology was developed the selection of an appropriate maximum ductile tearing, \( \Delta a_{\text{max}} \), to be used in the ECA analyses was discussed. \( \Delta a_{\text{max}} \) was used in the ECA analyses as one of the “stop” criteria in the analyses. Due to the special characteristics of this pipeline during operation, where the welds at the most critical location at the buckle crown are subjected to high “permanent” strain level (0.48%) and simultaneously exhibit high stress fatigue cycles, a \( \Delta a_{\text{max}} \) of 0.2 mm was recommended to ensure a safe and robust implementation of welding defect criteria. This section will attempt to describe and substantiate the selection of an appropriate maximum allowable ductile tearing, \( \Delta a_{\text{max}} \). There are basically two main types of ECA analyses:

- ECA Static
- ECA Fatigue

“ECA static” is applied when the load is increasing in a quasi-static way, i.e. when the stress or strain is steadily increasing until the critical condition is reached (a predefined critical CTOD, J or \( \Delta a \), leakage or rupture). This type of analyses is applied when a single or a few loading cycles occur, such as during reeling installation and design loads that may occur only once during operation of a pipeline (trawl impact, anchor dragging etc.). For these cases DNV-OS-F101, Appendix A, defines the methodology rather clear, also to what \( \Delta a_{\text{max}} \) is recommended to use. According to normal practice and recommendations, a maximum ductile tearing of 1 mm is applicable. In certain cases, where for instance later fatigue loads or high peak stresses during operation will not occur, a slightly higher maximum ductile tearing may be justified.

In “ECA Fatigue” fracture mechanics based fatigue assessments in the high-cycle regime shall be based on BS 7910:2005 or equivalent procedures. High-cycle loading is normally understood to be cycles of more than about 1000 and stress ranges in the elastic regime. This means that standard analysis using Paris’ law for crack growth can be used. The critical event will occur when the defect size reaches the critical size determined by Static ECA. This may be the case for fatigue during normal installation in the catenary and sag bend, where the number of cycles is fairly high and the stress ranges are medium high or during operation in free spans due to VIV, where the number of cycles is very high and stress ranges are low.

For low-cycle fatigue cases a well-defined, validated and generally accepted assessment procedure does not currently exist. Any method used for assessing low-cycle fatigue shall therefore be justified, well documented and agreed by all parties. The case studied in this paper must be characterized as a low cycle fatigue case, because the buckling stress ranges are high (up to above 300 MPa) and the fatigue occurs at very high continuous maximum stress level (535 MPa), in the elastic-plastic range close to the yield stress (yield stress is 539 MPa). The case can be illustrated as shown below in Figure 10a, where the stress cycles are given for the 2 first years and the last year. Total number of cycles is 513 for all 25 years. What happens with the fatigue crack growth in this case is unclear, at least when the defect size is approaching the critical size. It is doubtful that the standard Paris’ law equation is fully representative for this case. The VIV stress ranges which appear at the same locations will also add fatigue crack growth, however these are not shown in Figure 10a because they are in the stress range regime up to typically maximum 20-30 MPa. In addition, the pipeline is subjected to internal pressure, which affects the crack driving force at the maximum stress and may also result in higher fatigue crack growth rate.
The case would be completely different if the mean stress is lower, for instance \( \Delta \sigma_{\text{max}}/2 \) as illustrated in Figure 10b. In that case the ECA fatigue procedure as described above using the standard Paris’ law will be fully relevant. This will also be the case for fatigue at a lower maximum bending stress, such as for instance during installation.

All things considered, the results can be regarded as conservative, also because the global analyses were performed with a lower bound stress strain curve while the ECA analyses were done using an upper bound highest yield stress/tensile strength ratio and a lower bound tearing resistance curve. Furthermore, the maximum design temperature has been applied both for the global analyses and the ECA, which is also gives in conservative input data.

8. Conclusions

ECA of bimetal pipelines with different material stress strain behavior in the clad material, the backing steel and the weld metal have made it necessary to apply a finite element program such as LINKpipe to determine reliable and safe weld defect acceptance criteria. The present case with ECA of the as installed pipeline has shown that there are several input parameters that may greatly affect the defect criteria and it is essential to have as accurate input data as possible and carry out the design analyses to establish accurate input loads for the analyses (static stresses and strain as well as fatigue stresses).

Due to the 3 mm CRA clad layer on the internal surface with the purpose of providing corrosion resistance against the internal hydrocarbon fluid, the weld defect acceptance criteria are more stringent than on the outside or inside the weld (embedded defects) because internal surface defects are not allowed to grow by fatigue or ductile tearing through the 3 mm layer and into the backing carbon steel.

The analyses showed that even with conservative worst case selection of some of the input parameters (circumferential defect location, weld misalignment, maximum buckling strain, lower bound tearing resistance), it was possible to obtain acceptable weld defect criteria. Sensitivity analyses showed that the inherent safety factor is large for many of the input parameters when deviating slightly from the worst case value.

References